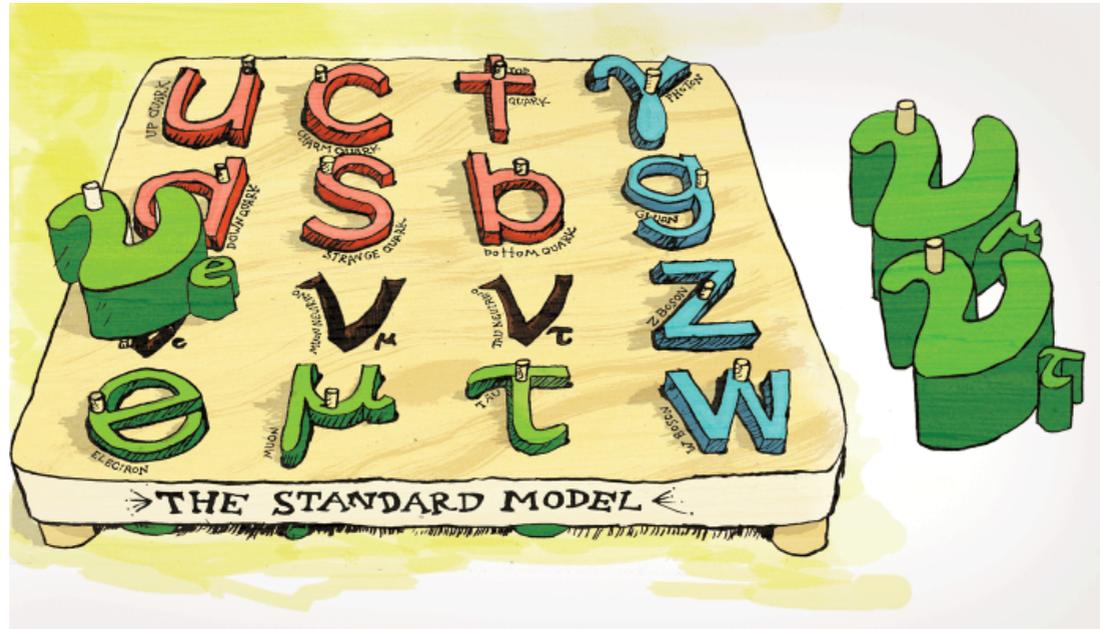


BSM in the Neutrino Frontier



Big Picture Neutrino Science Session

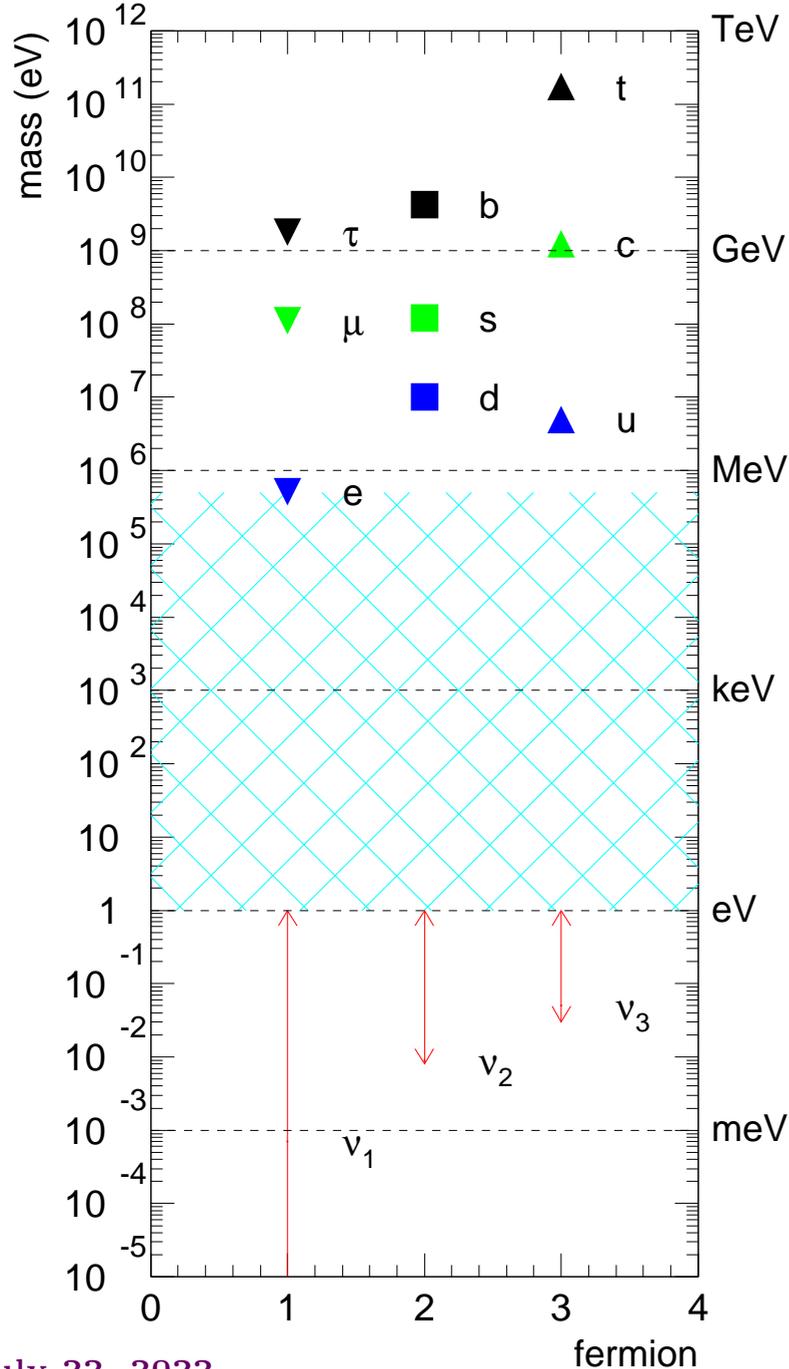
Community Summer Study – Snowmass – Seattle, July 17–26, 2022

André de Gouvêa – Northwestern University

Outline

- Neutrino masses: the BSM we know;
- More new physics in the neutrino sector;
- Neutrino experiments are BSM search engines;
- Are we already sitting on more new neutrino physics?

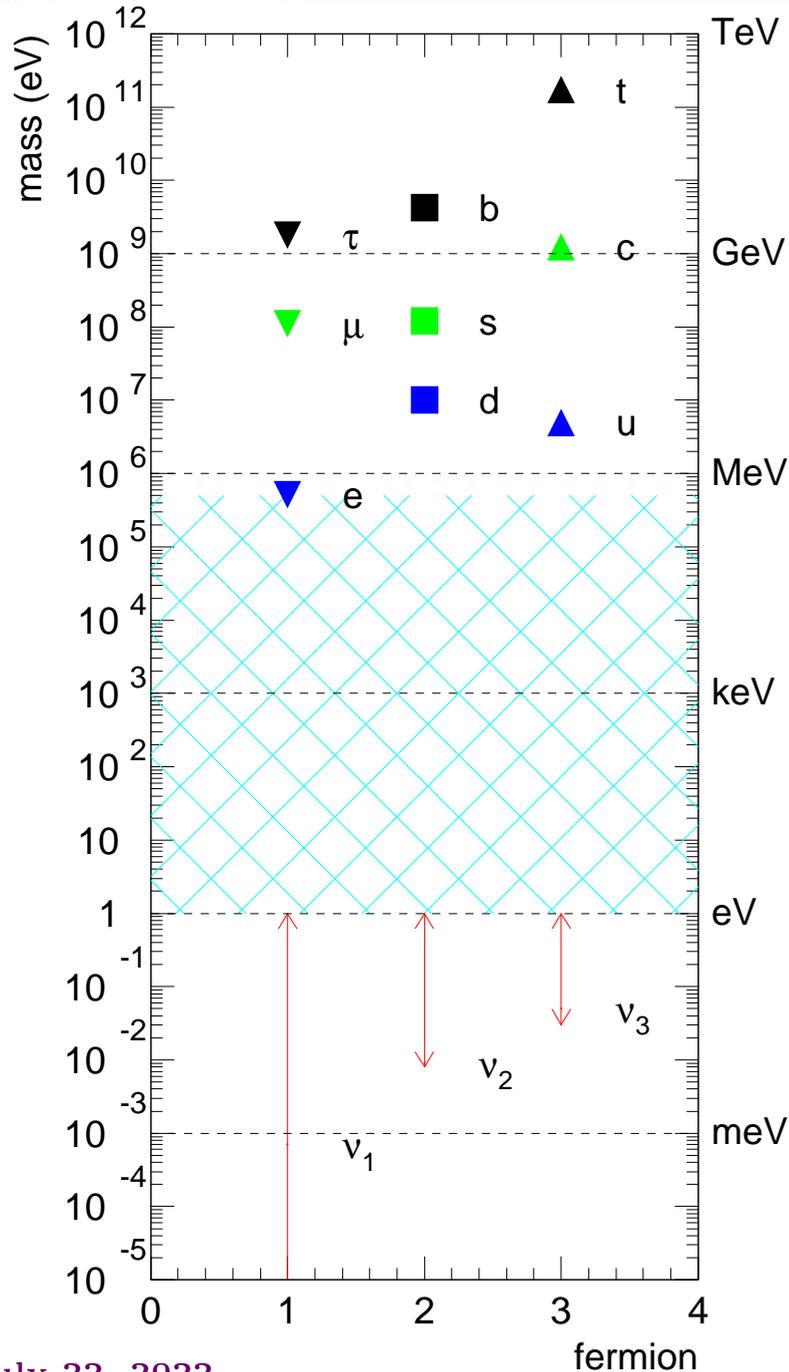
For much, much, more information and details, there were several NF and TF sessions dedicated to BSM and the Neutrino Frontier. And there are several white papers, including “White Paper on Light Sterile Neutrino Searches and Related Phenomenology,” arXiv:2203.07323 [hep-ex]; “The Present and Future Status of Heavy Neutral Leptons” arXiv:2203.08039 [hep-ph]; “Snowmass White Paper: Beyond the Standard Model effects on Neutrino Flavor” arXiv:2203.10811.



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEW PHYSICS

Nonzero neutrino masses imply the existence of new fundamental fields \Rightarrow **New Particles**

We know nothing about these new particles. They can be bosons or fermions, very light or very heavy, they can be charged or neutral, experimentally accessible or hopelessly out of reach...

There is only a handful of questions the standard model for particle physics cannot explain (these are personal. Feel free to complain).

- What is the physics behind electroweak symmetry breaking? (Higgs \checkmark).
- What is the dark matter? (not in SM).
- Why is there so much ordinary matter in the Universe? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM).

Neutrino Masses, Higgs Mechanism, and New Mass Scale of Nature

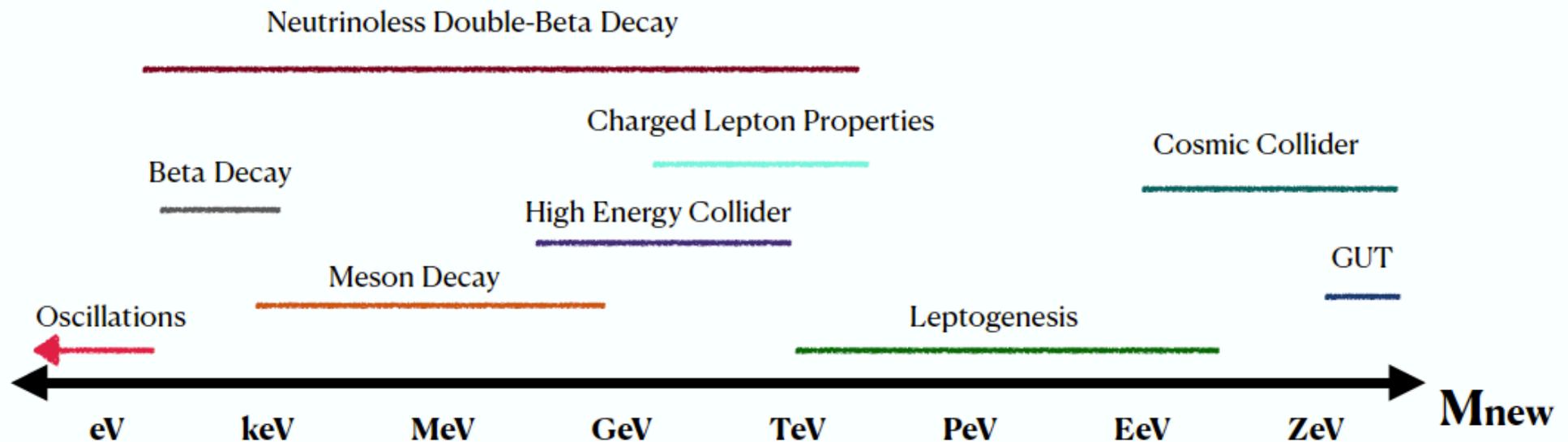
The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs doublet model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly**. And **lepton-number must be an exact symmetry** of nature (or broken very, very weakly);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking!;
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the **seesaw mechanism**.

We are going to need a lot of experimental information from all areas of particle physics in order to figure out what is really going on!

What Is the ν Physics Scale? We Have No Idea!



Different Mass Scales Are Probed in Different Ways, Lead to Different Consequences, and Connect to Different Outstanding Issues in Fundamental Physics.

Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts . . .

- understanding the fate of lepton-number. Neutrinoless double-beta decay.
- A comprehensive long baseline neutrino program.
- Probes of neutrino properties, including neutrino scattering experiments. And what are the neutrino masses anyway? Kinematical probes.
- Precision measurements of charged-lepton properties ($g - 2$, edm) and searches for rare processes ($\mu \rightarrow e$ -conversion the best bet at the moment).
- Collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- Neutrino properties affect, in a significant way, the history of the universe. These can be “seen” in cosmic surveys of all types.
- Astrophysical Neutrinos – Supernovae and other Galaxy-shattering phenomena. Ultra-high energy neutrinos and correlations with not-neutrino messengers.

HOWEVER...

We have only ever objectively “seen” neutrino masses in long-baseline oscillation experiments. It is one unambiguous way forward!

Does this mean we will reveal the origin of neutrino masses with oscillation experiments? We don't know, and we won't know until we try!

Furthermore, neutrino oscillation experiments are a unique environment to search for a variety of new phenomena, both neutrino-related and neutrino-not-so-related.

(NOTE: Due to time constraints, I will only concentrate on BSM searches in neutrino oscillation facilities. There is fascinating, unique, and very promising BSM physics that is accessible to many other topics directly related to the Neutrino Frontier! [$0\nu\beta\beta$, β -decay and other weak, nuclear processes, UHE-neutrinos, supernova neutrinos, neutrino scattering, etc.])

More New Physics in the Neutrino Sector?



since $m_\nu \neq 0$ and leptons mix ...

More New Physics in the Neutrino Sector?

- New neutrino states. In this case, e.g., the 3×3 mixing matrix would not be unitary.
- New short-range neutrino interactions. These lead to, for example, new matter effects. If we don't take these into account, there is no reason for the three flavor paradigm to “close.”
- New, unexpected neutrino properties. Do they have nonzero magnetic moments? Do they decay? [The answer is ‘yes’ to both, but nature might deviate dramatically from expectations from the SM plus massive neutrinos.]
- Weird stuff. CPT-violation. Decoherence effects (aka “violations of Quantum Mechanics.”)
- etc.

Case Study – A Fourth Neutrino

If there are more neutrinos with a well-defined mass, it is easy to extend the paradigm:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_? \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \cdots \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \cdots \\ U_{?1} & U_{?2} & U_{?3} & U_{?4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$

- New mass eigenstates easy: ν_4 with mass m_4 , ν_5 with mass m_5 , etc.
- What are these new “flavor” (or weak) eigenstates $\nu_?$? Here, the answer is we don’t care. We only assume there are no new accessible interactions associated to these states.

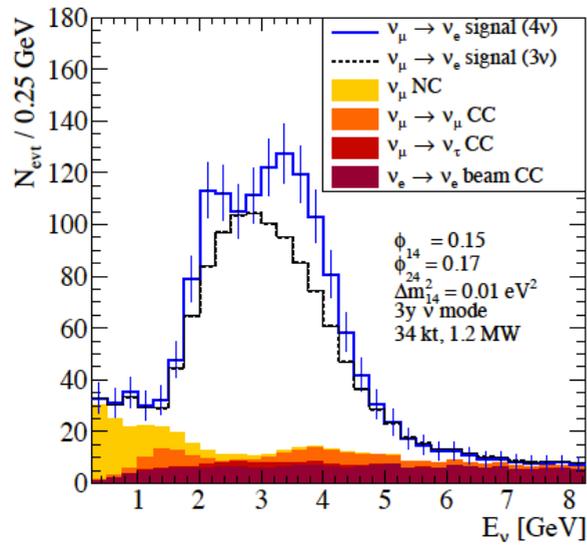
$$\begin{aligned}
U_{e2} &= s_{12}c_{13}c_{14}, \\
U_{e3} &= e^{-i\eta_1} s_{13}c_{14}, \\
U_{e4} &= e^{-i\eta_2} s_{14}, \\
U_{\mu 2} &= c_{24} (c_{12}c_{23} - e^{i\eta_1} s_{12}s_{13}s_{23}) - e^{i(\eta_2-\eta_3)} s_{12}s_{14}s_{24}c_{13}, \\
U_{\mu 3} &= s_{23}c_{13}c_{24} - e^{i(\eta_2-\eta_3-\eta_1)} s_{13}s_{14}s_{24}, \\
U_{\mu 4} &= e^{-i\eta_3} s_{24}c_{14}, \\
U_{\tau 2} &= c_{34} (-c_{12}s_{23} - e^{i\eta_1} s_{12}s_{13}c_{23}) - e^{i\eta_2} c_{13}c_{24}s_{12}s_{14}s_{34} \\
&\quad - e^{i\eta_3} (c_{12}c_{23} - e^{i\eta_1} s_{12}s_{13}s_{23}) s_{24}s_{34}, \\
U_{\tau 3} &= c_{13}c_{23}c_{34} - e^{i(\eta_2-\eta_1)} s_{13}s_{14}s_{34}c_{24} - e^{i\eta_3} s_{23}s_{24}s_{34}c_{13}, \\
U_{\tau 4} &= s_{34}c_{14}c_{24}.
\end{aligned}$$

When the new mixing angles ϕ_{14} , ϕ_{24} , and ϕ_{34} vanish, one encounters oscillations among only three neutrinos, and we can map the remaining parameters $\{\phi_{12}, \phi_{13}, \phi_{23}, \eta_1\} \rightarrow \{\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}\}$.

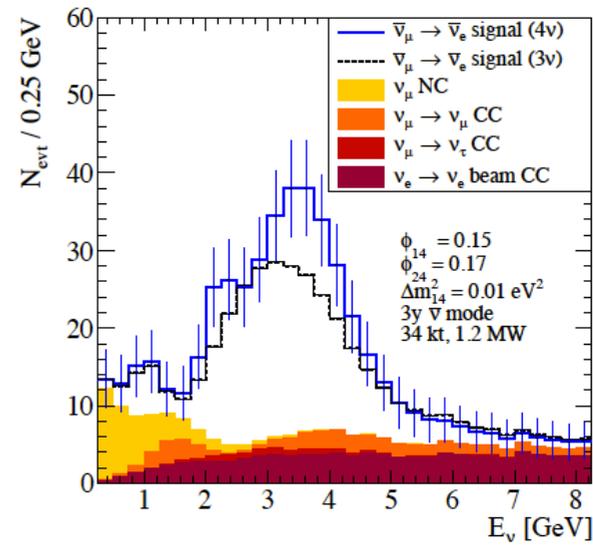
Also

$$\eta_s \equiv \eta_2 - \eta_3,$$

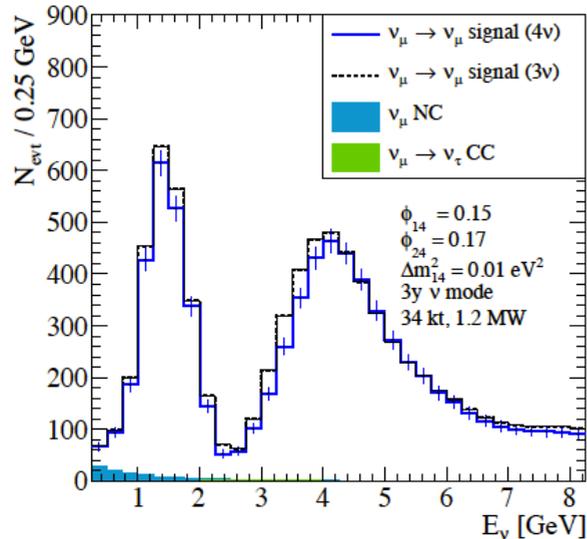
is the only new CP-odd parameter to which oscillations among ν_e and ν_μ are sensitive.



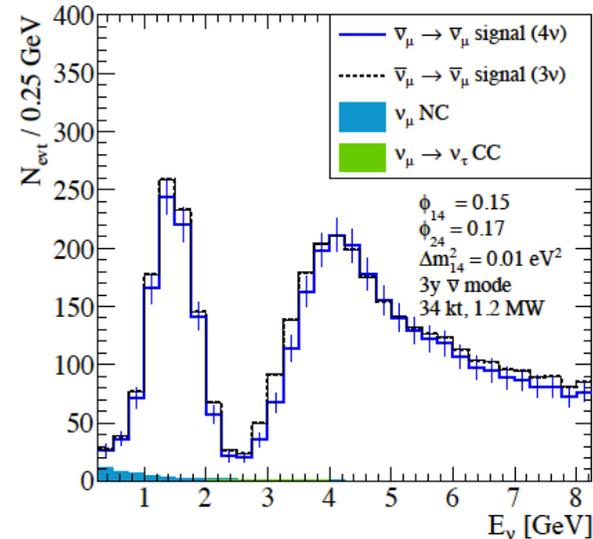
(a)



(b)



(c)



(d)

[Berryman et al, arXiv:1507.03986]

FIG. 1: Expected signal and background yields for six years (3y ν + 3y $\bar{\nu}$) of data collection at DUNE, using fluxes projected by Ref. [1], for a 34 kiloton detector, and a 1.2 MW beam. (a) and (b) show appearance channel yields for neutrino and antineutrino beams, respectively, while (c) and (d) show disappearance channel yields. The 3 ν signal corresponds to the standard three-neutrino hypothesis, where $\sin^2 \theta_{12} = 0.308$, $\sin^2 \theta_{13} = 0.0235$, $\sin^2 \theta_{23} = 0.437$, $\Delta m_{12}^2 = 7.54 \times 10^{-5} \text{ eV}^2$, $\Delta m_{13}^2 = 2.43 \times 10^{-3} \text{ eV}^2$, $\delta_{CP} = 0$, while the 4 ν signal corresponds to $\sin^2 \phi_{12} = 0.315$, $\sin^2 \phi_{13} = 0.024$, $\sin^2 \phi_{23} = 0.456$, $\sin^2 \phi_{14} = 0.023$, $\sin^2 \phi_{24} = 0.030$, $\Delta m_{14}^2 = 10^{-2} \text{ eV}^2$, $\eta_1 = 0$, and $\eta_s = 0$. Statistical uncertainties are shown as vertical bars in each bin. Backgrounds are defined in the text and are assumed to be identical for the three- and four-neutrino scenarios: any discrepancy is negligible after accounting for a 5% normalization uncertainty.

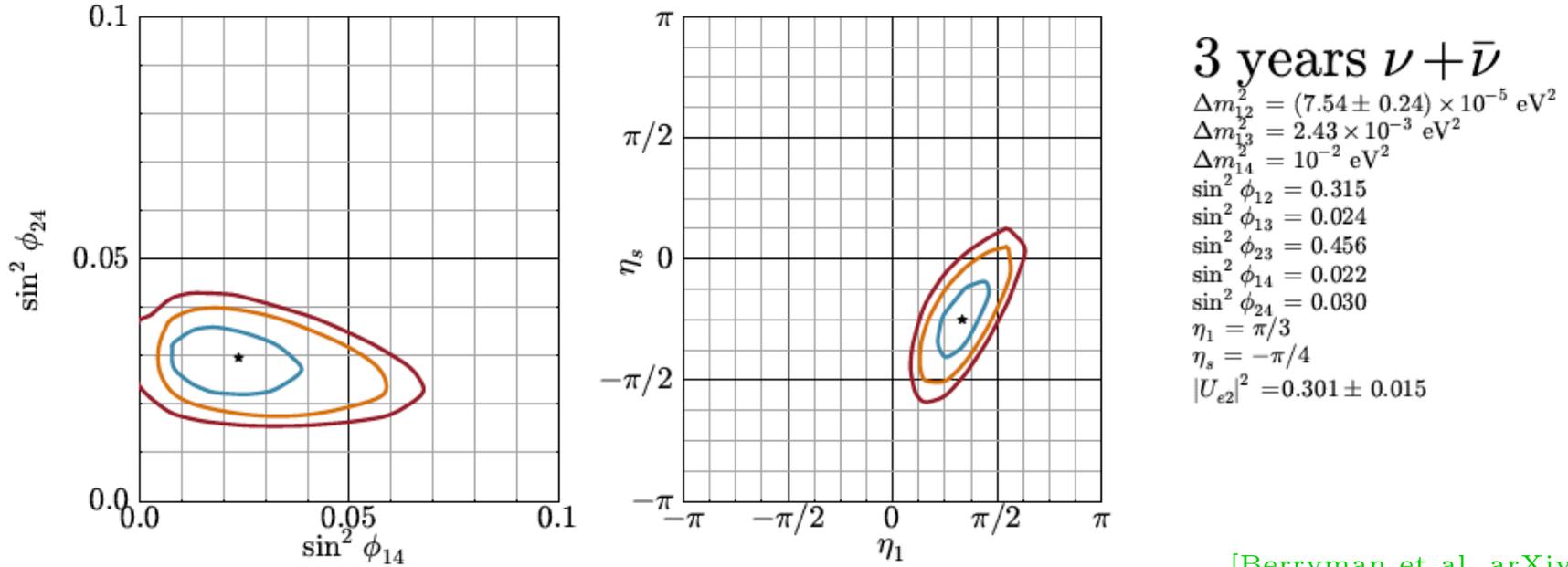
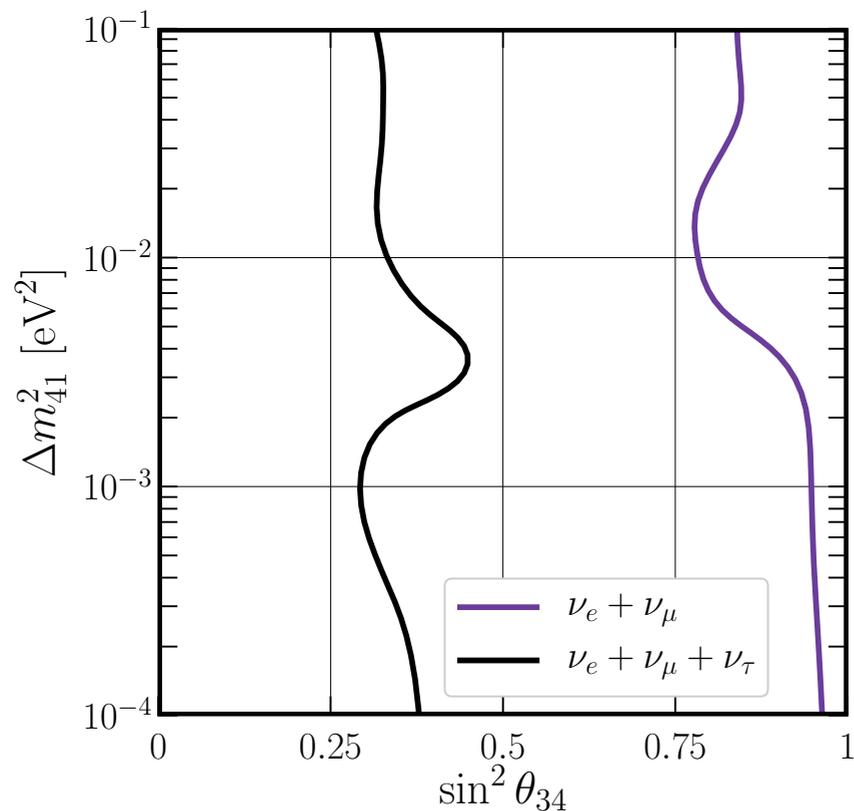


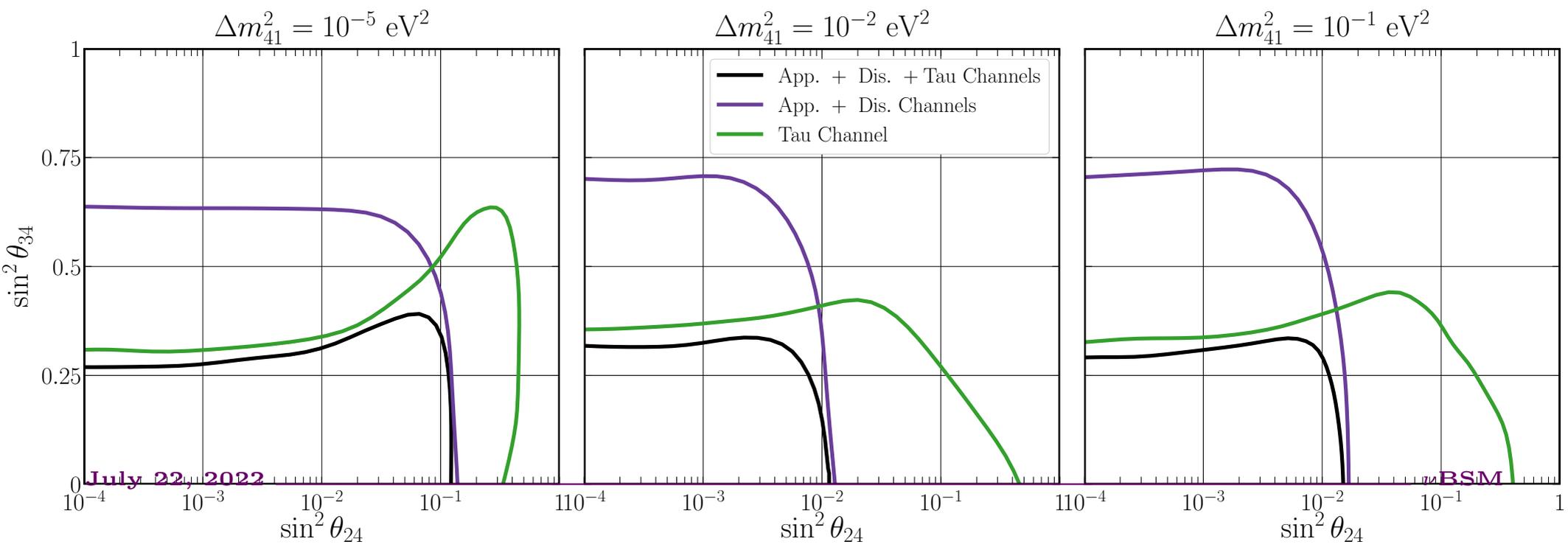
FIG. 5: Expected sensitivity contours at 68.3% (blue), 95% (orange), and 99% (red) CL at DUNE with six years of data collection ($3y \nu + 3y \bar{\nu}$), a 34 kiloton detector, and a 1.2 MW beam given the existence of a fourth neutrino with parameters from Case 2 in Table I. Results from solar neutrino experiments are included here as Gaussian priors for the values of $|U_{e2}|^2 = 0.301 \pm 0.015$ and $\Delta m_{12}^2 = 7.54 \pm 0.24 \times 10^{-5} \text{ eV}^2$ [22].

A

Northwestern

Impact of Including ν_τ Appearance

[AdG, Kelly, Pasquini, Stenico, arXiv:1904.07265]



Case Study – Non-Standard Neutrino Interactions (NSI)

Effective Lagrangian (assuming new interaction is neutral-current-like):

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta) \sum_{f=e,u,d} (\epsilon_{\alpha\beta}^{fL}\bar{f}_L\gamma^\rho f_L + \epsilon_{\alpha\beta}^{fR}\bar{f}_R\gamma^\rho f_R) + h.c.,$$

For oscillations,

$$H_{ij} = \frac{1}{2E_\nu} \text{diag} \{0, \Delta m_{12}^2, \Delta m_{13}^2\} + V_{ij},$$

where

$$V_{ij} = U_{i\alpha}^\dagger V_{\alpha\beta} U_{\beta j},$$

$$V_{\alpha\beta} = A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix},$$

$A = \sqrt{2}G_F n_e$. $\epsilon_{\alpha\beta}$ are linear combinations of the $\epsilon_{\alpha\beta}^{fL,R}$. In the literature, it is common to consider propagation effects only and ignore NSI effects in production or detection (ϵ versus ϵ^2).

The Physics Behind NSI – Comments and Concerns

There are two main questions associated to NSI's. They are somewhat entwined.

1. Are there models for new physics that lead to large NSIs? Are these models well motivated? Are they related to some of the big questions in particle physics?
2. Are NSIs constrained by observables that have nothing to do with neutrino physics? Are large NSI effects allowed at all?

The Physics Behind NSI – Comments and Concerns

There are two main questions associated to NSI's. They are somewhat entwined.

1. Are there models for new physics that lead to large NSIs? Are these models well motivated? Are they related to some of the big questions in particle physics?

[ans: Yes. They can be. They can be.]

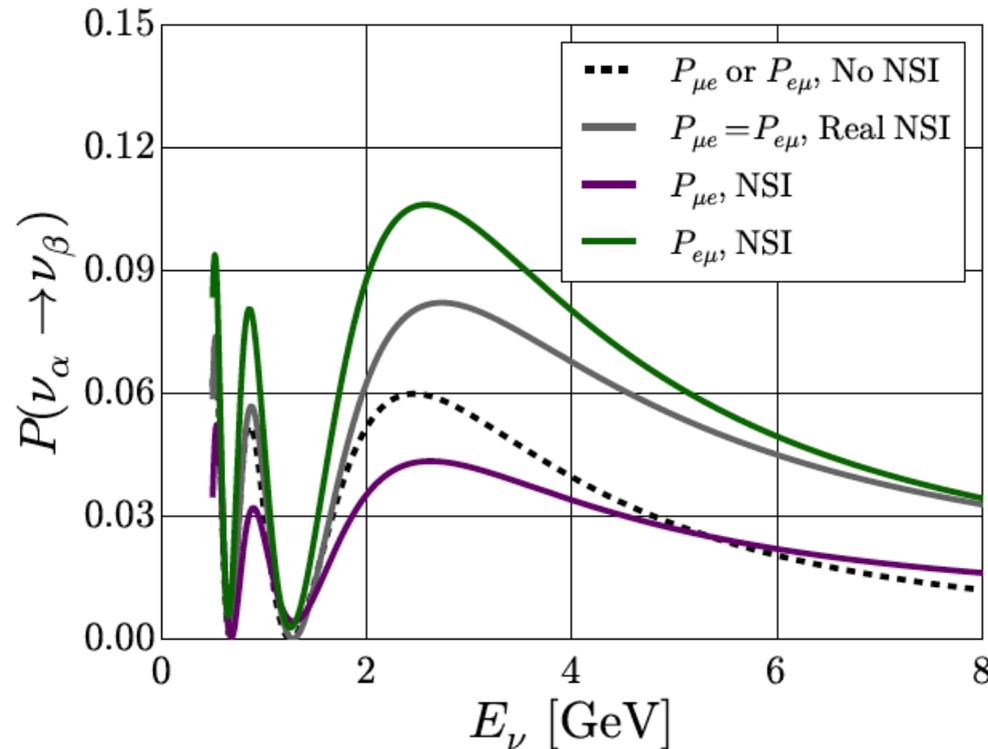
2. Are NSIs constrained by observables that have nothing to do with neutrino physics? Are large NSI effects allowed at all?

[ans: Absolutely. Yes, but it is model dependent.]

See Overview by Y. Farzan and M. Tórtola, [arXiv:1710.09360 \[hep-ph\]](#)

For a concrete UV-complete model, see K.S. Babu et al, [arXiv:1705.01822 \[hep-ph\]](#)

There are new sources of CP-invariance violation! [easier to see T-invariance violation]



[AdG and Kelly, arXiv:1511.05562]

FIG. 2: T -invariance violating effects of NSI at $L = 1300$ km for $\epsilon_{e\mu} = 0.1e^{i\pi/3}$, $\epsilon_{e\tau} = 0.1e^{-i\pi/4}$, $\epsilon_{\mu\tau} = 0.1$ (all other NSI parameters are set to zero). Here, the three-neutrino oscillation parameters are $\sin^2 \theta_{12} = 0.308$, $\sin^2 \theta_{13} = 0.0234$, $\sin^2 \theta_{23} = 0.437$, $\Delta m_{12}^2 = 7.54 \times 10^{-5}$ eV², $\Delta m_{13}^2 = 2.47 \times 10^{-3}$ eV², and $\delta = 0$, i.e., no “standard” T -invariance violation. The green curve corresponds to $P_{e\mu}$ while the purple curve corresponds to $P_{\mu e}$. If, instead, all non-zero NSI are real ($\epsilon_{e\mu} = 0.1$, $\epsilon_{e\tau} = 0.1$, $\epsilon_{\mu\tau} = 0.1$), $P_{e\mu} = P_{\mu e}$, the grey curve. The dashed line corresponds to the pure three-neutrino oscillation probabilities assuming no T -invariance violation (all $\epsilon_{\alpha\beta} = 0$, $\delta = 0$).

Telling Different Scenarios Apart:

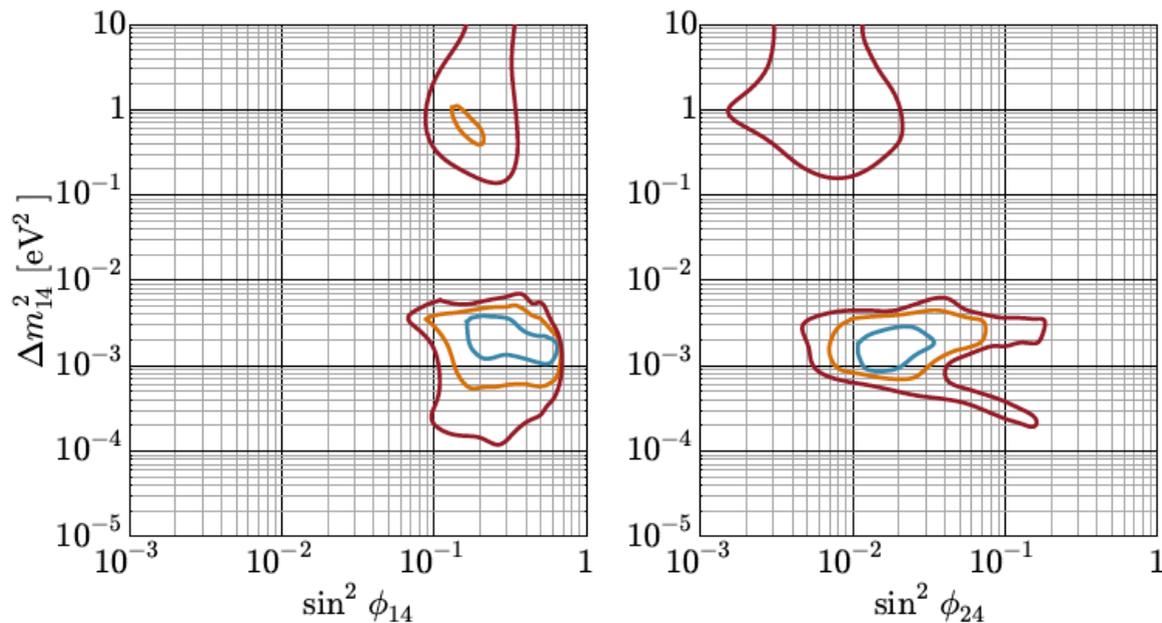
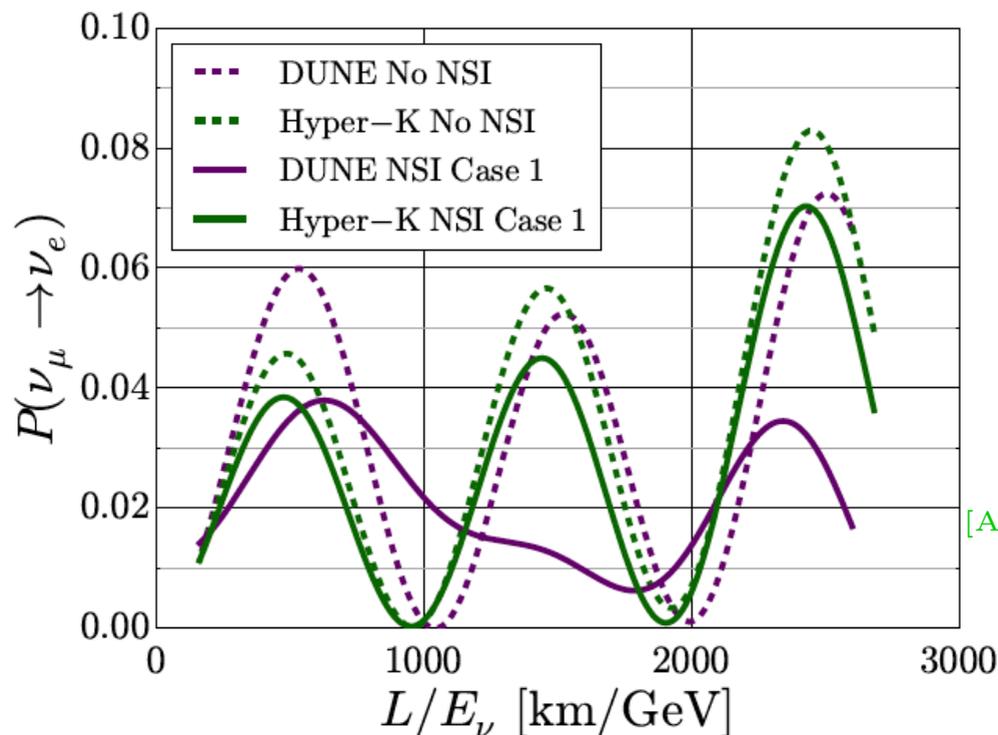


FIG. 8: Sensitivity contours at 68.3% (blue), 95% (orange), and 99% (red) for a four-neutrino fit to data consistent with Case 2 from Table I. All unseen parameters are marginalized over, and Gaussian priors are included on the values of Δm_{12}^2 and $|U_{e2}|^2$. See text for details.

[AdG and Kelly, arXiv:1511.05562]

How Do We Learn More – Different Experiments!

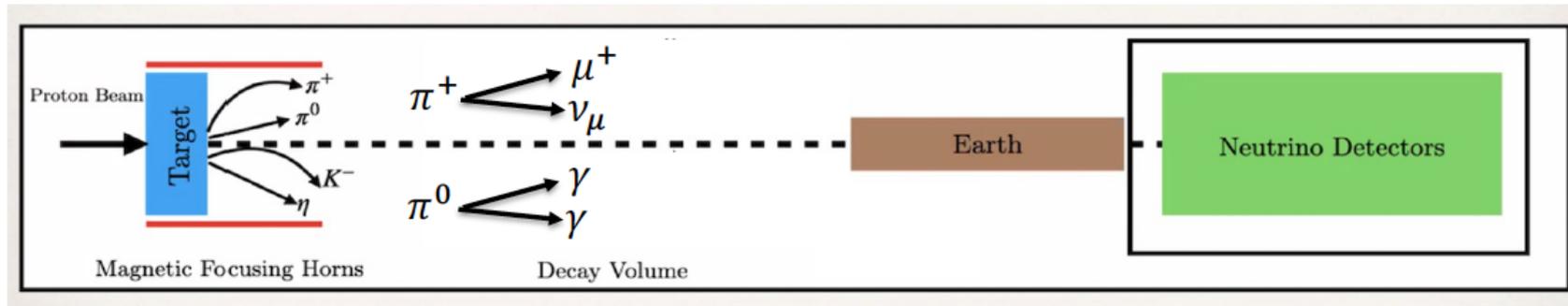
- Different L and E , same L/E (e.g. HyperK versus DUNE);
- Different matter potentials (e.g. atmosphere versus accelerator);
- Different oscillation modes (e.g., appearance versus disappearance, e 's, μ 's and τ 's).



[AdG and Kelly, arXiv:1511.05562]

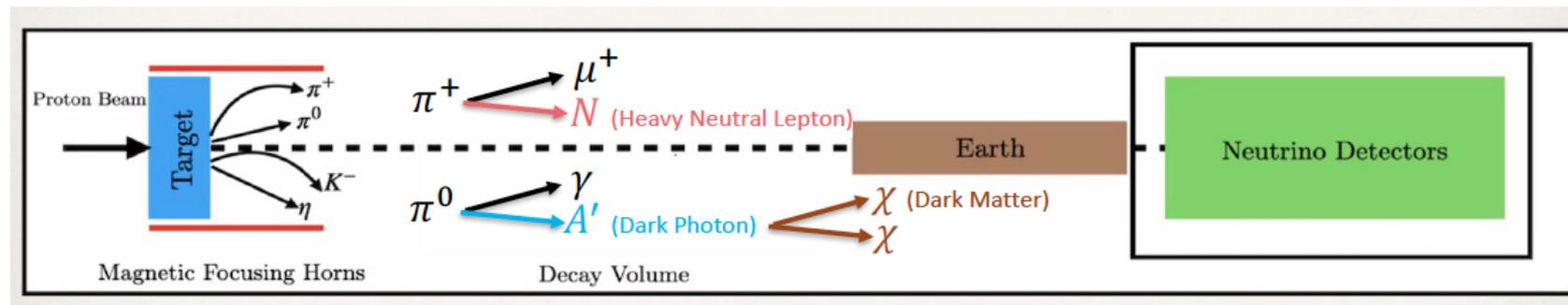
FIG. 9: Oscillation probabilities for three-neutrino (dashed) and NSI (solid) hypotheses as a function of L/E_ν , the baseline length divided by neutrino energy, for the DUNE (purple) and HyperK (green) experiments. Here, $\delta = 0$ and the three-neutrino parameters used are consistent with Ref. [47].

Neutrino Oscillation Experiments as BSM Search Engines – Dark Sectors



Credit: Kevin Kelly

The huge fluxes of neutrinos and photons can be used for BSM searches

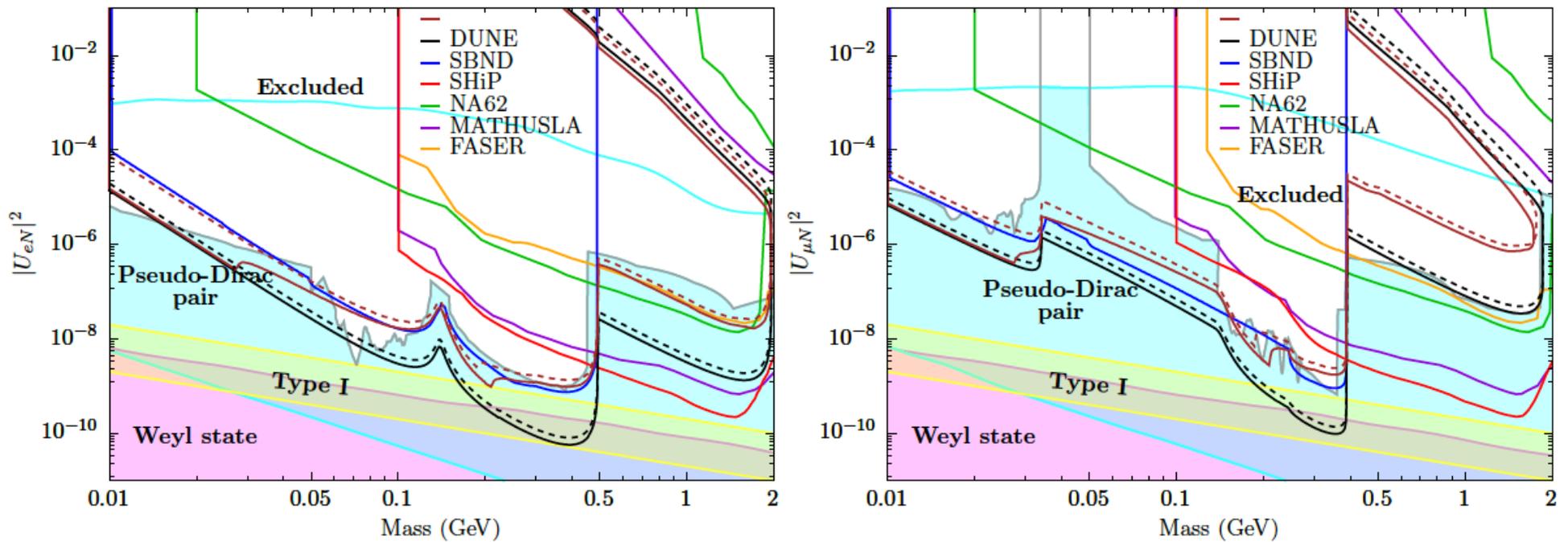


- Heavy Neutral Leptons, Dark Photon, light DM, etc

Berryman et al, PRD (2018)
 Breitbach et al, JHEP (2022)
 De Romeri et al, PRD (2019)
 Magill et al, PRL (2019)

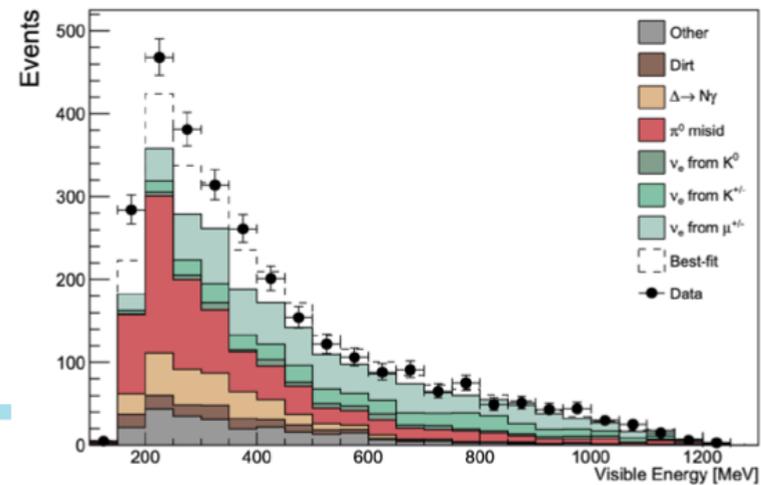
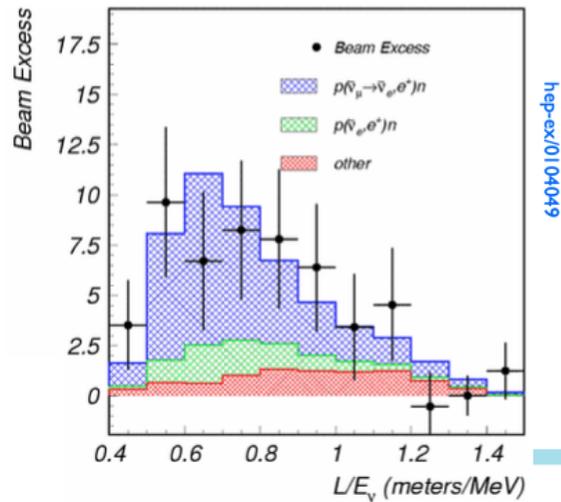
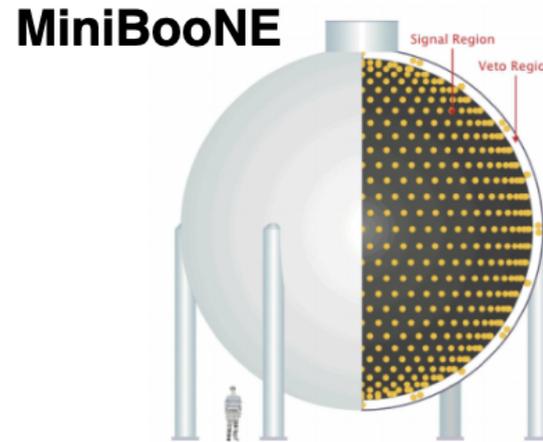
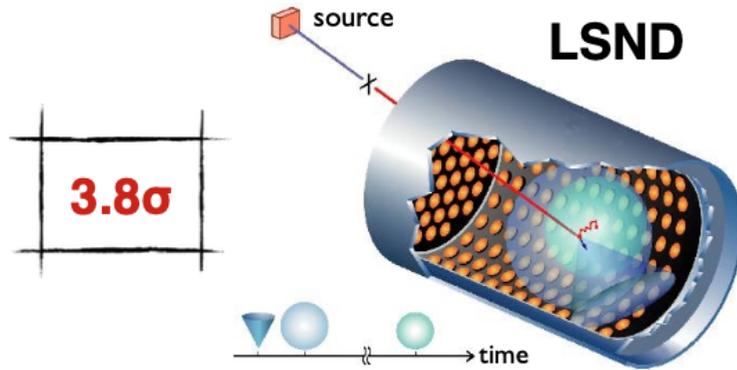
[Courtesy of Z. Tabrizi]

Example: Heavy Neutral Leptons – Testing the Seesaw Mechanism!



[Ballett et al, arXiv:1905.00284]

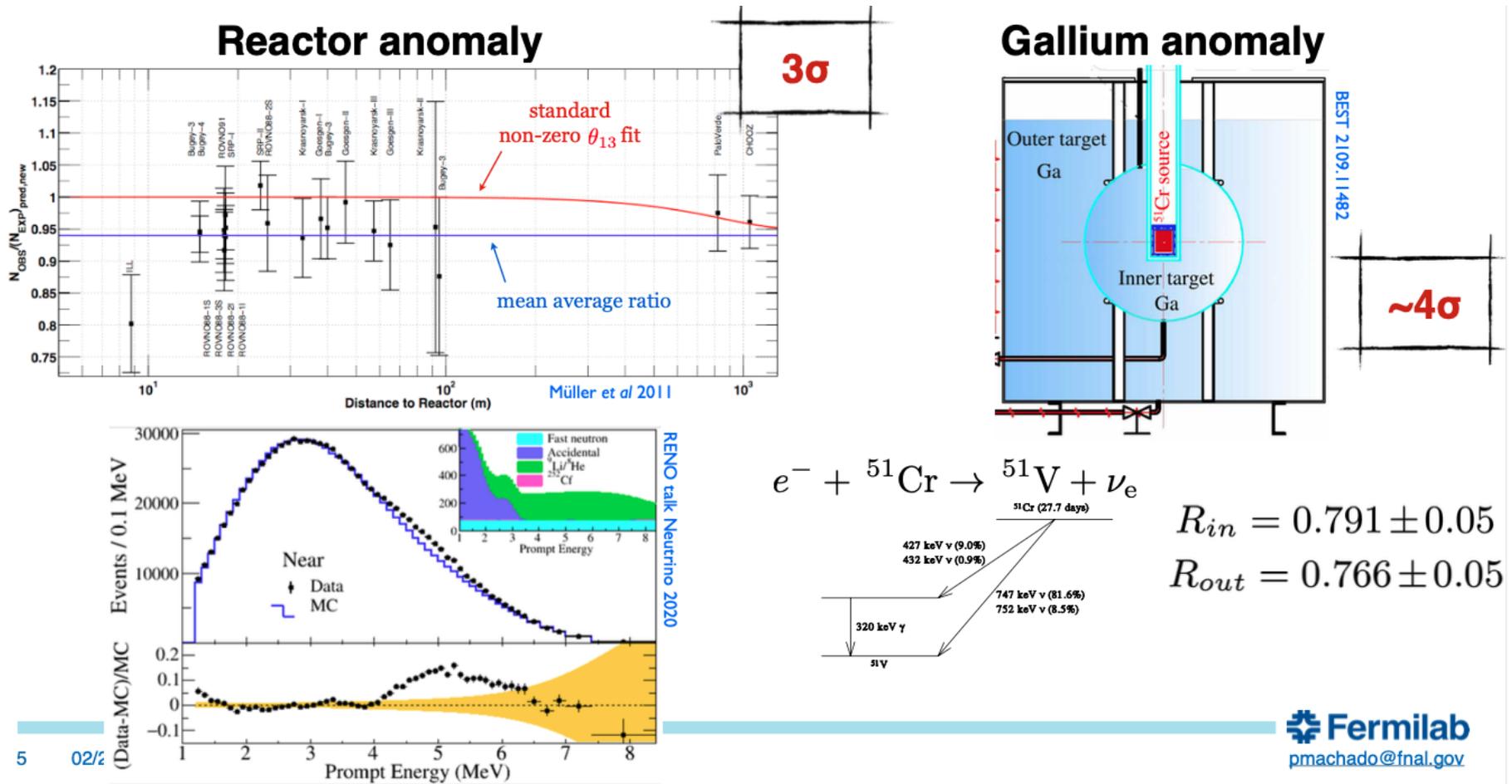
Are We Sitting on More New Neutrino Physics?



Fermilab
chado@fnal.gov

[P. Machado talk at TF Workshop]

Are We Sitting on More New Neutrino Physics?

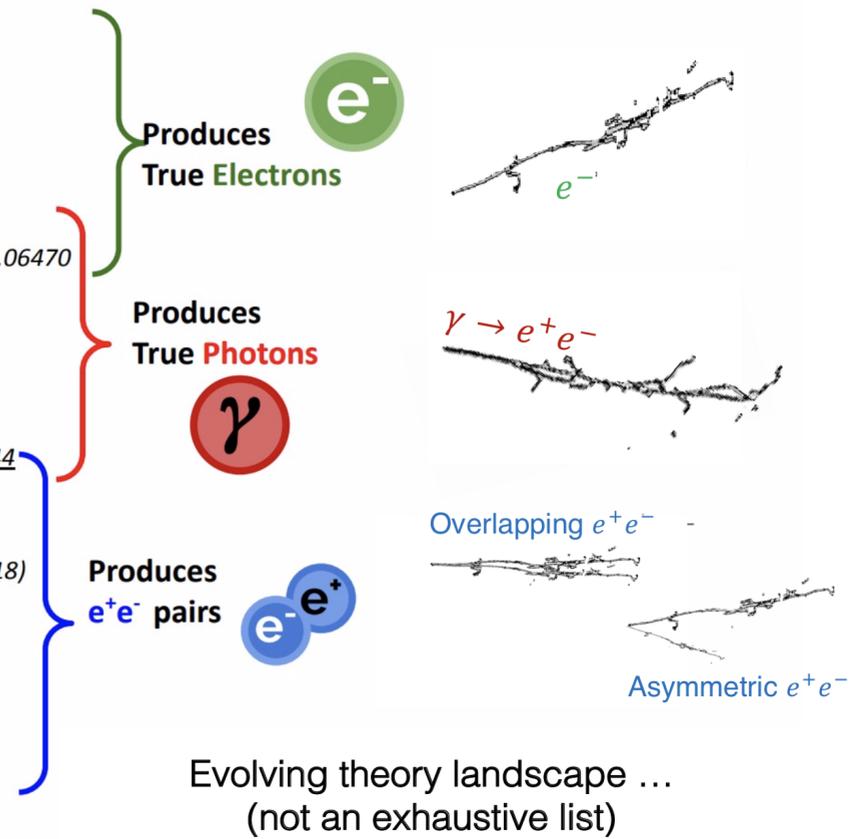


[P. Machado talk at TF Workshop]

Is it BSM? Lots of possibilities. For example...

More exploration of MiniBooNE excess

- Decay of O(keV) Sterile Neutrinos to active neutrinos
 - [13] Dentler, Esteban, Kopp, Machado *Phys. Rev. D* 101, 115013 (2020)
 - [14] de Gouvêa, Peres, Prakash, Stenico *JHEP* 07 (2020) 141
- New resonance matter effects
 - [5] Asaadi, Church, Guenette, Jones, Szelc, *PRD* 97, 075021 (2018)
 - [16] Alves, Louis, deNiverville, [\[hep-ph\]2201.00876 \(2022\)](#)
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
 - [7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, [arXiv:2105.06470](#)
- Decay of heavy sterile neutrinos produced in beam
 - [4] Gninenko, *Phys.Rev.D*83:015015,2011
 - [12] Alvarez-Ruso, Saul-Sala, *Phys. Rev. D* 101, 075045 (2020)
 - [15] Magill, Plestid, Pospelov, Tsai *Phys. Rev. D* 98, 115015 (2018)
 - [11] Fischer, Hernandez-Cabezudo, Schwetz, *PRD* 101, 075045 (2020)
 - [17] Dutta, Kim, Thompson, Thornton, Van de Water [\[hep-ph\]2110.11944](#)
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
 - [1] Bertuzzo, Jana, Machado, Zukanovich Funchal, *PRL* 121, 241801 (2018)
 - [2] Abdullahi, Hostert, Pascoli, *Phys.Lett.B* 820 (2021) 136531
 - [3] Ballett, Pascoli, Ross-Lonergan, *PRD* 99, 071701 (2019)
 - [10] Dutta, Ghosh, Li, *PRD* 102, 055017 (2020)
 - [6] Abdallah, Gandhi, Roy, *Phys. Rev. D* 104, 055028 (2021)
- Decay of axion-like particles
 - [8] Chang, Chen, Ho, Tseng, *Phys. Rev. D* 104, 015030 (2021)
- A model-independent approach to any new particle
 - [9] Brdar, Fischer, Smirnov, *PRD* 103, 075008 (2021)

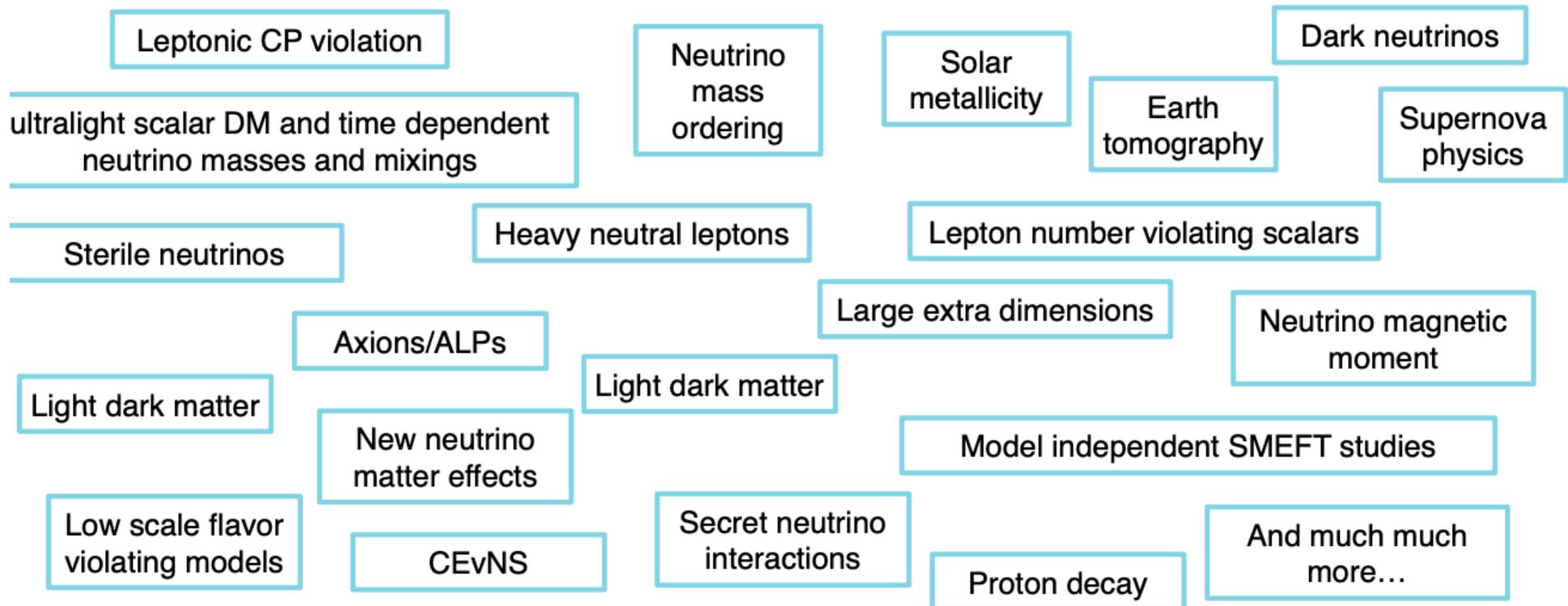


[MicroBooNE talk at Neutrino 2022]

A lot I did not talk about...

What is new in BSM related to neutrinos?

The range of standard and beyond standard physics that can be probed in these experiments is large and in accelerated expansion



Summary

- Neutrino masses: the BSM we know;

We know very little about the new physics behind nonzero neutrino masses. Neutrino experiments and non-neutrino experiments can help. There are no guarantees.

- More new physics in the neutrino sector;

Massive neutrinos are allowed other new properties and neutrino oscillation experiments allow one to look for more new physics in the neutrino sector.

- Neutrino experiments are BSM search engines;

Intense beams of charged and neutral mesons. Lots of neutrinos (pile-up!). With a capable near-detector complex, and assuming we understand neutrino scattering well enough, there are unique opportunities to explore the unknown.

- Are we already sitting on more new neutrino physics?

We don't know, but we think we know how to find out. Stay tuned!

Backup Slides . . .

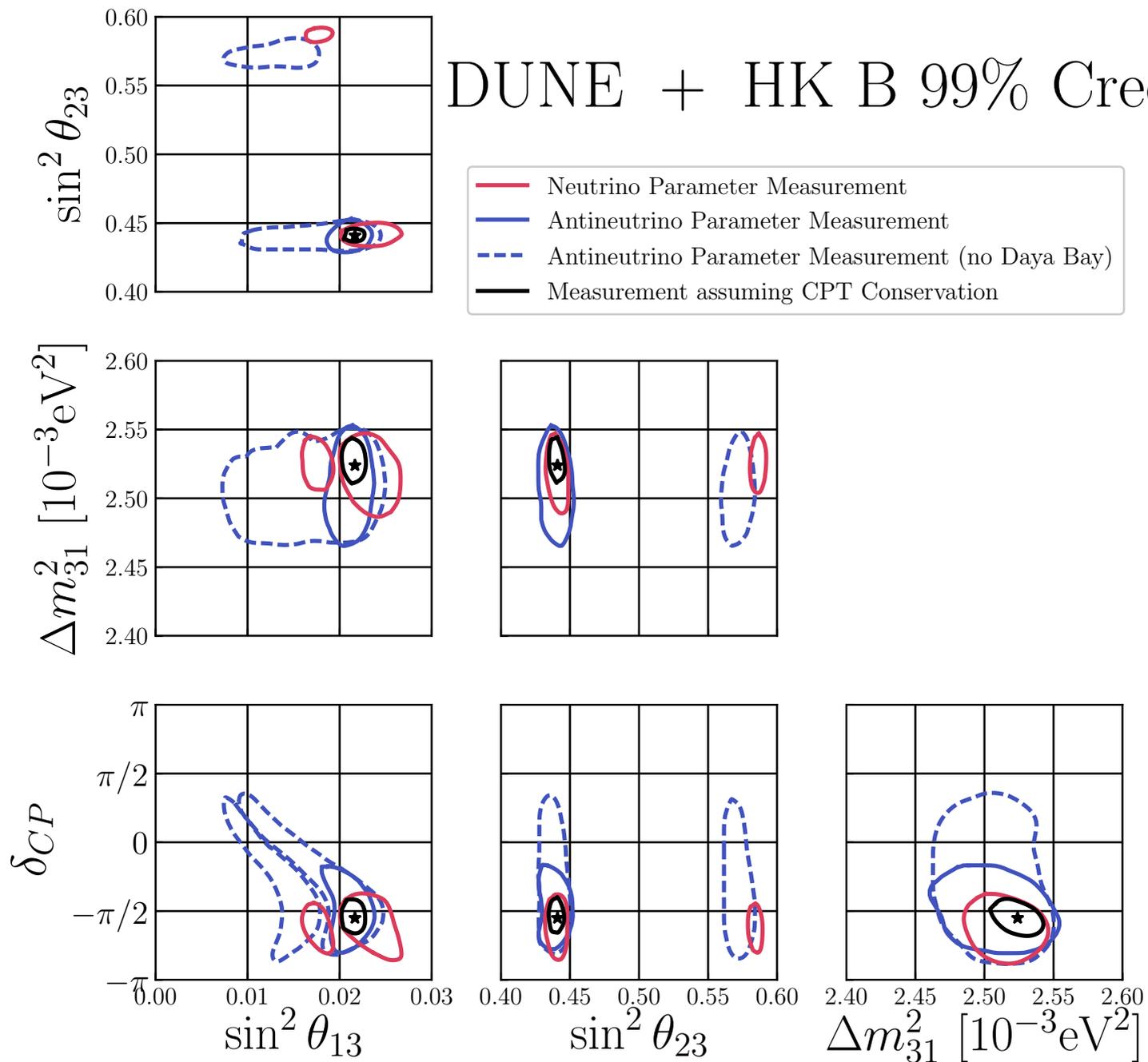


Different Oscillation Parameters for Neutrinos and Antineutrinos?

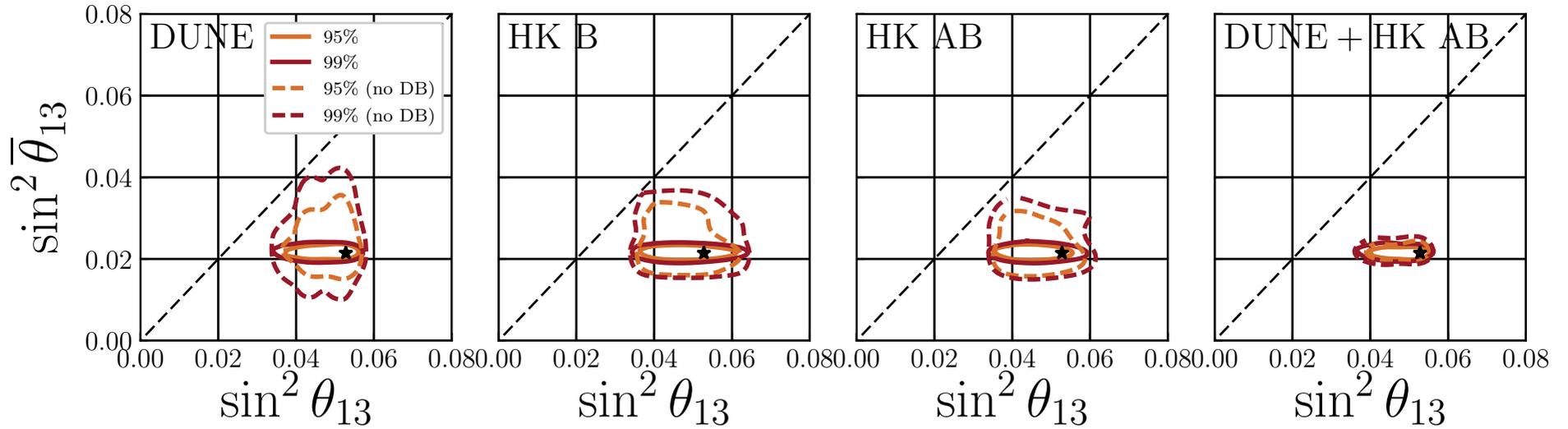
[AdG, Kelly, arXiv:1709.06090]

- How much do we know, independently, about neutrino and antineutrino oscillations?
- What happens if the parameters disagree?

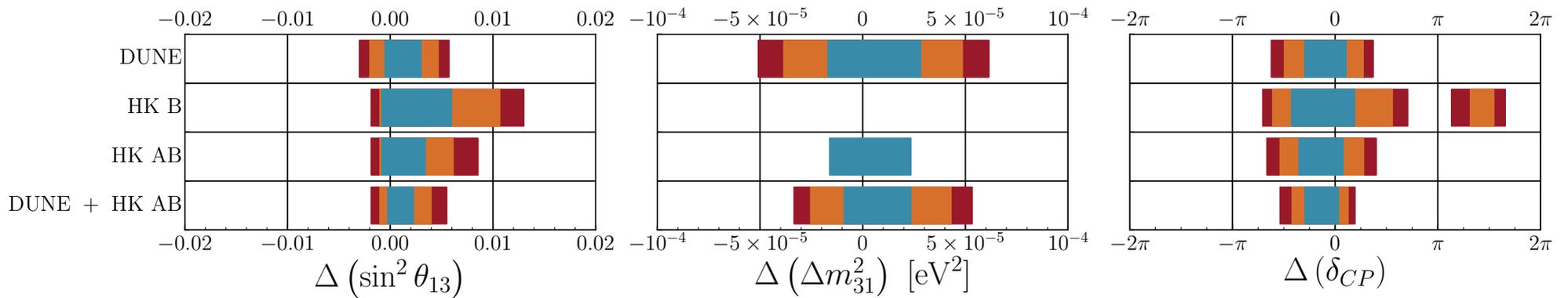
DUNE + HK B 99% Cred.



[AdG and Kelly, arXiv:1709.06090]



[AdG and Kelly, arXiv:1709.06090]



Some technicalities for the aficionados

- 34 kiloton liquid argon detector;
- 1.2 MW proton beam on target as the source of the neutrino and antineutrino beams, originating 1300 km upstream at Fermilab;
- 3 years each with the neutrino and antineutrino mode;
- Include standard backgrounds, and assume a 5% normalization uncertainty;
- Whenever quoting bounds or measurements of anything, we marginalize over all parameters not under consideration;
- We include priors on Δm_{12}^2 and $|U_{e2}|^2$ in order to take into account information from solar experiments and KamLAND. Unless otherwise noted, we assume the mass ordering is normal;
- We do not include information from past experiments. We assume that DUNE will “out measure” all experiments that came before it (except for the solar ones, as mentioned above).

The Physics Behind NSI – Comments and Concerns

There are two main questions associated to NSI's. They are somewhat entwined.

1. What is the new physics that leads to neutrino NSI? or are there models for new physics that lead to large NSIs? Are these models well motivated? Are they related to some of the big questions in particle physics?
2. Are NSIs constrained by observables that have nothing to do with neutrino physics? Are large NSI effects allowed at all?

Effective Lagrangian:

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\bar{f}\gamma^\rho f).$$

This is not $SU(2)_L$ invariant. Let us fix that:

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{L}_\alpha\gamma_\rho L_\beta)(\bar{f}\gamma^\rho f).$$

where $L = (\nu, \ell^-)^T$ is the lepton doublet. This is a big problem.

Charged-Lepton flavor violating constraints are really strong (think $\mu \rightarrow e^+e^-e^+$, $\mu \rightarrow e$ -conversion, $\tau \rightarrow \mu$ +hadrons, etc), and so are most of the flavor diagonal charged-lepton effects.

There are a couple of ways to circumvent this...

1. Dimension-Eight Effective Operator

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\bar{f}\gamma^\rho f).$$

This is not $SU(2)_L$ invariant. Let us fix that **in a different way**

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\frac{\epsilon^{\alpha\beta}}{v^2}((HL)_\alpha^\dagger\gamma_\rho(HL)_\beta)(\bar{f}\gamma^\rho f).$$

where $HL \propto H^+\ell^- - H^0\nu$. After electroweak symmetry breaking $H^0 \rightarrow v + h^0$ and we only get new neutrino interactions.

Sadly, it is not that simple. At the one-loop level, the dimension-8 operator will contribute to the dimension-6 operator in the last page, as discussed in detail in [Gavela *et al*, arXiv:0809.3451 [hep-ph]]. One can, however, fine-tune away the charged-lepton effects.

2. Light Mediator

(Overview by Y. Farzan and M. Tórtola, arXiv:1710.09360 [hep-ph])

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\bar{f}\gamma^\rho f).$$

This may turn out to be a good effective theory for neutrino propagation but a bad effective theory for most charged-lepton processes. I.e.

$$\mathcal{L}^{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{\alpha\beta}(\bar{L}_\alpha\gamma_\rho L_\beta)(\bar{f}\gamma^\rho f).$$

might be inappropriate for describing charged-lepton processes if the particle we are integrating out is light (as in lighter than the muon).

Charged-lepton processes are “watered down.” Very roughly

$$\epsilon \rightarrow \epsilon \left(\frac{m_{Z'}}{m_\ell} \right)^2$$

where $m_{Z'}$ is the mass of the particle mediating the new interaction, and m_ℓ is the mass associated to the charged-lepton process of interest.